STINFO COPY

AFRL-HE-WP-TR-2007-0017

Helmet Tracker Requirements and Measurement Verification

Gary Martinsen
Judson Shattuck
Jeffrey Craig

Air Force Research Laboratory
Human Effectiveness Directorate
Wright-Patterson AFB OH 45433-7022

February 2007

Final Report for the period October 2002 to March 2007

Approved for public release; distribution is unlimited.

Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Interface Division
Battlespace Visualization Branch
Wright-Patterson AFB OH 45433

NOTICE AND SIGNATURE PAGE

TECHNICAL REVIEW AND APPROVAL

AFRL-HE-WP-TR-2007-0017

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

FOR THE DIRECTOR

//signed//
DANIEL G. GODDARD
Chief, Warfighter Interface Division
Air Force Research Laboratory

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
09 Feb 2007

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
October 2002 to March 2007

4. TITLE AND SUBTITLE
Helmet Tracker Requirements and Measurement Verification

5a. CONTRACT NUMBER
In-House

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62202F

6. AUTHOR(S)
Gary Martinsen
Judson Shattuck
Jeffrey Craig

5d. PROJECT NUMBER
7184

5e. TASK NUMBER
11

5f. WORK UNIT NUMBER
21

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Materiel Command
Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Interface Division
Battlespace Acoustics Branch
Wright Patterson AFB OH 45433-7901

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/HECV

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-HE-WP-TR-2007-0017

12. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

AFRL/PA Cleared 2/27/07 AFRL/WS-07-0423.

14. ABSTRACT
A helmet tracker is a critical element in the path that delivers targeting and other sensor data to the user of a helmet-mounted display (HMD) in a military aircraft. This paper reviews helmet tracker technology with respect to use in military aviation. The human factors limitations of helmet tracker systems for delivering both targeting and flight reference information to a military pilot are also discussed. This paper also presents data collected from the Dynamic Tracker Test Apparatus (DTTA). The DTTA was designed by the Helmet Mounted Sensory Technology (HMST) laboratory to accurately measure azimuth rotation in both static and dynamic conditions.

15. SUBJECT TERMS
Helmet tracker, helmet-mounted display, dynamic tracker measurement, static tracker measurement

16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Jeffrey Craig
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U	SAR	22	19b. TELEPONE NUMBER (*Include area code*)

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI-Std Z39-18

This page blank intentionally.

TABLE OF CONTENTS

LIST OF FIGURES iv
LIST OF TABLES iv
1. SUMMARY 1
2. INTRODUCTION 2
    2.1 The Tracker/HMD System 2
        2.1.1 Magnetic trackers 3
        2.1.2 Optical trackers 3
        2.1.3 Acoustic trackers 3
        2.1.4 Inertial hybrid trackers 4
    2.2 Uses of Helmet-Tracked Data 4
        2.2.1 HMD targeting information 4
        2.2.2 Flying information 4
    2.3 Human Factor Issues of Helmet Trackers 4
        2.3.1 Noise issues 5
        2.3.2 Accuracy issues 5
        2.3.3 Timing issues 5
    2.4 Previous Human Factors Studies of Tracked Systems 6
3. DYNAMIC TRACKER TEST APPARATUS EVALUATION 6
    3.1 System Description 7
    3.2 Data Acquisition 9
    3.3 System Operation 9
    3.4 Static Characterization 10
        3.4.1 Spool characterization without head tracker equipment installed 10
    3.5 Dynamic Characterization 12
        3.5.1 Determination of head rotation rates 12
        3.5.2 Dynamic characterization of the DTTA 13
4. CONCLUSIONS 13
5. REFERENCES 15

LIST OF FIGURES

Figure 1. Schematic of a simplified HMD/tracker system 3
Figure 2. Dynamic tracker test apparatus (top view)... 7
Figure 3. Dynamic tracker test apparatus (front view)... 8
Figure 4. DTAA with emitter pack installed 9
Figure 5. Axis of motion 9
Figure 6. Average elevation versus periphery position -180° to 180°.. 10
Figure 7. Average spool flatness versus periphery position 11
Figure 8. Average elevation changes due to spindle movement, bending, etc. (after flatness removed).. 11
Figure 9. Induced azimuth and elevation error due to reference frame misalignment in elevation.. 12
Figure 10. Dynamic Rotation of DTTF.. 13

LIST OF TABLES

Table 1. Rates and head rotations when the head with helmet and 2 pound NVG ballast is rotated about the Z axis 13

1. SUMMARY

A helmet tracker is a critical element in the path that delivers targeting and other sensor data to the user of a helmet-mounted display (HMD) in a military aircraft. The original purpose of an HMD was to serve as a helmet-mounted sight and to provide a means to fully utilize the capabilities of off-boresight munitions. Recently, the role of the HMD has evolved from being strictly a targeting tool to providing detailed flight path and situation awareness information. These changes, however, have placed even greater value on the visual information that is transferred through the helmet tracker to the HMD. Specifically, the timeliness and accuracy of the information, which is of critical importance when the HMD is used as a targeting aid, is of even greater importance when the HMD is used to display flight reference information. This is especially relevant since it has been proposed to build new military aircraft without a physical head-up display (HUD) and to display HUD information virtually with an HMD. In this paper, we review the current state of helmet tracker technology with respect to use in military aviation. We also identify the parameters of helmet trackers that offer the greatest risk when using an HMD to provide information beyond targeting data to the user. The human factors limitations of helmet tracker systems for delivering both targeting and flight reference information to a military pilot are also discussed.

This paper also presents data collected from the Dynamic Tracker Test Apparatus (DTTA). The DTTA was designed by the Helmet Mounted Sensory Technology (HMST) laboratory to accurately measure azimuth rotation in both static and dynamic conditions. The DTTA was characterized for static position data at various increments through a 360° sweep and for speeds up to 1000°/sec or 17.45 rad/sec. This paper describes the design, construction, capabilities, limitations, characterization, and performance of the DTTA.

2. INTRODUCTION

The incorporation of the HUD into military fast-jets provided a technological revolution that dramatically increased a pilot's ability to utilize critical visual information. This information was previously available only in head-down displays if it was available at all. With the HUD, the pilot could view an array of targeting and attitude information while constantly looking outside the aircraft. However, the relatively small area of the outside world that was covered by the HUD imagery limited information transfer from the HUD. To visually acquire an air-to-air (A/A) or air-to-ground (A/G) target, a pilot often had to look well away from the HUD. Once a target was located, the pilot had to orient the jet in the direction of the target until it was in an area covered by the HUD. The development of the HMD provided a novel solution to this problem, especially with respect to targeting information. Using an HMD, the pilot could acquire and lock onto targets that were well outside the field that was covered by the HUD information. A logical expansion of using an HMD to present targeting data was to use it to present other forms of visual information. Some recent studies have demonstrated significant benefits of using the HMD to present attitude and other situation awareness information while a pilot is accomplishing off-boresight tasks[1-4].

While the insertion of HMDs into fast-jets expanded the boundaries of visual information that could be delivered, it was not devoid of problems. For example, pilots were often able to direct their head, and thus the HMD, toward a target at a faster rate than the sensor of the chosen weapon could be slewed. In this case, the target designator (TD) box lagged behind the direction of the head and had to catch up. As pointed out by Kranz[5], this latency in weapon sensor slewing could cause a dangerous situation if friendly aircraft were in the area.

As indicated above, HMDs might also be used to display information other than targeting data to the pilot. Presenting attitude information on the HMD during off-boresight tasks has been shown to increase pilots' viewing time away from the HUD[4]. Because the attitude information was always available, the pilot spent more time off-boresight searching for targets. Recently, the possibility of presenting all head-up visual information via the HMD in military fast-jets has been investigated[6]. In this case, the HMD will replace the HUD and the visual information that was previously shown on the HUD will be displayed on the HMD.

HMD visual information is displayed relative to the position of the pilot's head and direction of view. To accomplish this, the position of the helmet must be tracked. As has been documented[6], the incorporation of helmet trackers in military aircraft raises many complex issues. To start with, trackers are not perfect. For example, trackers have a limited area over which they will function. However, much of the complexity in tracker use arises from the fact that a human is in the loop. A pilot must be able to utilize tracked HMD information in a safe and efficient manner. Inaccuracies, delays, or other complications might compromise the pilot's ability to utilize the information.

The goal of many developers is to make trackers as fast and error free as possible. While these goals are worthwhile, they might be overkill or, conversely, they might be insufficient. Unfortunately, the human factors requirements for tracked HMD information are not known. In this paper, we review trackers and the human factors requirements for using HMD information that has been processed through a tracker.

2.1 The Tracker/HMD System

When discussing helmet tracker issues, one must decide whether to consider the tracker in isolation or to consider it as part of an overall system. In isolation, trackers may have specifications that would not seem to be of great concern from a human factors point of view. When considered as part of a system, other issues arise that are important to consider. For example, the angular resolution for a specific tracker may be a low value of 0.01°. But, the benefit of this high resolution tracker might be diminished in a helmet-tracker system (HTS) if a low-resolution display were part of the system. Similar arguments can be made for the other tracker specifications such as update rate and latency.

Figure 2 shows a block diagram of a simplified HTS. The actual tracker components are only in the top three blocks on this diagram. The overall system, however, is much more complicated. To illustrate, a sensor detects a target and symbology representing this event is displayed on the HMD. The pilot moves his or her head to acquire the target and the resulting head movement is interpreted by the helmet tracker. The armament computer receives the relative helmet position, processes the data, and slews the weapon sensor to the new location. The new location of the weapon sensor is returned by the HTS and displayed on the HMD. This process is repeated until a conclusion is reached.

There are several types of trackers, categorized by the underlying tracker technology, that have been used, are used, or have the potential to be used in military aircraft[7,8]. These tracker technologies include magnetic, optical, acoustic, and inertial hybrid.

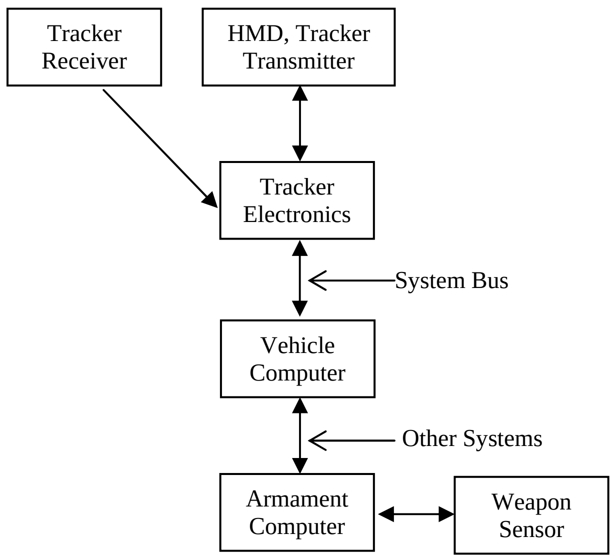

Figure 1. Schematic of a simplified HMD/tracker system.

2.1.1 Magnetic trackers

Magnetic tracker technology has reached a level of sophistication to merit its use in military fast-jets. The Joint Helmet-Mounted Cueing System, a helmet/HMD system that is in the process of being fielded, employs a magnetic tracker. A magnetic tracker radiates a magnetic field and helmet position in a cockpit is determined by comparing the position of the tracker receiver within the field to that of a model[8]. One of the drawbacks of magnetic technology is that extensive cockpit mapping is required. In addition, other magnetic sources or metal in the cockpit can distort the magnetic field.

2.1.2 Optical trackers

Optical helmet trackers work by transmitting light from fixed sources to receivers on the helmet or vice versa. Data from many transmitter/receiver combinations are usually required to calculate helmet position. A primary advantage of optical trackers is that cockpit mapping is not required. Disadvantages include their vulnerability to direct signal obstruction, signal interference by other lights (e.g., sunlight), and night vision goggle incompatibility. In addition, strict alignment of the helmet-mounted receivers is required. If the helmet flexes, the receivers will change position leading to calculation errors.

2.1.3 Acoustic trackers

Acoustic, or ultrasonic, trackers share many of the same advantages and disadvantages of optical trackers. Highly accurate position data are possible without first mapping the cockpit. However, interference by other acoustic sources and blockage of the transmitters or receivers are potential problems. As with optical trackers, movement of the acoustic receivers (or transmitters) secondary to helmet flexure is a potential source of error.

2.1.4 Inertial hybrid trackers

Inertial trackers are usually used in combination with another tracker technology. Inertial trackers can relay positional data at very high rates. Their main shortcoming is that exact positional data are subject to drift. Therefore, hybrid trackers that use an inertial tracker in combination with another technology (e.g., magnetic, acoustic) are being developed. For example, the magnetic component of an inertial-magnetic hybrid tracker would be used to update the positional data of the inertial component.

2.2 Uses of Helmet-Tracked Data

There are two broad classes of visual information that can be displayed in an HTS those being targeting and flying.

2.2.1 HMD targeting information

One of the goals for the development of the HTS was to use it in a helmet-mounted cuing system (HMCS). A HMCS extended the dynamic targeting range beyond the targeting abilities of the HUD. HMD targeting falls into two categories which are air-to-air (A/A) and air-to-ground (A/G). In A/A targeting, the pilot is directed to an airborne target, either by visual acquisition or by indication by an onboard sensor. The pilot uses the HMD to place a TD box on or close to the moving target so that the weapon may lock onto the target. Achievement of lock-on requires sufficient update rate, low delay, and high accuracy by the HTS. The pilot uses the HMD to acquire and lock onto a ground target in an A/G task. Unlike A/A targets that are frequently moving at a high rate of speed, A/G targets are stationary or moving relatively slowly. Thus, the process of moving a TD box to acquire an A/G target would seem relatively easy. However, just the opposite may be true because a TD box over a stationary ground target needs to be stabilized over the target. This space stabilization of the target designator will be difficult in a high vibration environment where the aircraft, the pilot, and the HMD system are all experiencing high frequency motion.

2.2.2 Flying information

Numerous scenarios can be envisioned where an HMD might be used to deliver flight path, situation awareness, and similar visual information to a pilot. These scenarios include displaying aircraft data while viewing off-boresight and using the HMD as a primary flight reference. In fact, the Joint Strike Fighter has been designed without a HUD meaning that the visual information that was previously presented on the HUD will be displayed on an HMD. The delivery of timely and accurate data is of critical importance when the pilot is looking off-boresight. This importance is magnified when the HMD is used to present information that is stabilized with respect to the jet (e.g., on a virtual HUD). A few situations where very fast and highly accurate presentation of tracked HMD imagery would be required are take-offs and landings, nap-of-the-earth flying, and unusual attitude recovery

In a HUD-less jet, the HMD will be used to present some or all the images that were previously on the HUD during take-offs and landings. In a HUD equipped aircraft, the HUD is physically attached to the jet and HUD symbology is displayed in a specified area. HMD imagery that serves as a virtual HUD will need to appear fixed in a similar space. In addition, moving symbols will need to appear to move smoothly, as they do on a HUD. Achieving these goals might be difficult because HMD images are formed using the helmet visor and the visor is in constant motion. If the visor is in rapid motion (e.g., during vibration or buffeting), very high update rates and low lags of the HTS will be required to display symbology that does not appear to jitter.

2.3 Human Factors Issues of Helmet Trackers

There are several issues that are imperative to address when using an HTS in a fast-jet. Some of the more important issues include system noise (static and dynamic), accuracy (static and dynamic), and timing. Timing issues include system update rate (or refresh rate) and latency (lag, delay).

2.3.1 Noise issues

Noise has many definitions. Noise can refer to a disturbance in any communication system. In electronics and engineering, noise refers to any disturbances that do not represent part of the signal[9]. Static noise in an HTS can limit the resolution, stability, and accuracy of the transmitted signal. Most tracker manufactures do not directly report static noise. There are important parameters that could be affected by static noise including resolution (position, angular, and static), stability (position and angular), and accuracy (static and absolute). Noise that affects any of these specifications has the potential to introduce error and uncertainty during targeting or flying tasks when using an HTS.

Dynamic noise is often associated with high frequency jitter of the HMD symbology in an aircraft that is experiencing vibration or buffeting. In this sense, it may not be true noise as defined above but may be related to tracker timing issues (see below). Filtering can be used to ameliorate the symbology jitter but may have the unwanted side effect of introducing additional delay into the system[6].

2.3.2 Accuracy issues

Accuracy is one of the most critical human factors issues to address when using a tracker in the cockpit. Many elements of an HTS serve to limit accuracy, or contribute to inaccuracy. In fact, Cogan[10] has described 11 distinct categories of an HTS that are important when considering accuracy. An inaccurate placement of a TD box may increase the time required to lock on to a target. Inaccurate attitude information or flight path marker direction could lead to loss of situation awareness during certain flying tasks. Any of these inaccuracies would increase the workload on the pilot.

Static accuracy is reported in terms of position accuracy (x,y,z) and angular or orientation accuracy (pitch, roll, yaw). Static inaccuracy could cause errors in the position of a TD box during a targeting task and errors in the position of a path marker during flying tasks. At a distance of 10 km, an orientation inaccuracy of 0.5° translates to pointing inaccuracy of about 87 m. An inaccuracy of this magnitude might be significant during targeting tasks.

Comparable to dynamic noise, dynamic accuracy is also related to tracker timing issues. Dynamic inaccuracy can arise from delay in a tracker system. It also includes any static inaccuracies in the system. Consider, for example, a case where a pilot moves his or her head quickly to acquire an A/A target. The TD box lags behind because it cannot keep up with the movement of the head. The direction of the TD box is inaccurate until it catches up with head direction.

2.3.3 Timing issues

Tracker timing issues cause perhaps the most significant human factors concerns when using an HTS in a fast-jet. This is reflected by the fact that most of the human factors studies of HTS and related areas have been primarily concerned with timing issues. There are two separate but related areas under timing issues: update rate and latency. These two areas are usually not examined individually, but are grouped together in most human factors studies of HTS.

Delays in the delivery of visual information by a cockpit HTS might cause several problems, including dynamic inaccuracy, as discussed above. Lagged data might cause a significant increase in workload for a pilot and thereby decrease his or her ability to fly and fight. The ability to lock onto potential targets and to fly to specific waypoints may be reduced in situations where the HMD symbology doesn't respond with head or aircraft movements.

As stated by Adelstein, Johnston, and Ellis[11], update rate is a distinct quantity that is different from latency. Update rate for a specific component can be thought of as the number of samples that are sent forward or displayed over a given time period. In most cases, the update rate for a system such as an HTS is the time it takes to update the slowest component of the system. Update rates of system components are not necessarily synchronized and update rates of a component are not necessarily constant.

Latency in a tracked system can be difficult to delineate and has been defined in many ways[11,12]. The overall system latency of a tracker system in a virtual environment is the time elapsed from motion of the user's head until representation of that movement in the display, in one definition[11]. The overall latency of an HTS can be represented by the following formula:

Overall system latency = cycle time + transmission time + processing time

where cycle time equals the reciprocal of the update rate. The formula shows that the overall latency has more sources of delay than simply update rate. The additional delay sources increase the time it takes for sampled data to be displayed on the HMD, meaning that the symbology may be several cycles old when displayed.

2.4 Previous Human Factors Studies of Tracked Systems

Many studies examining the human factors effects of delays of visual imagery in flight simulators have been accomplished. In addition, there is a good amount of literature documenting problems associated with the use of trackers in virtual reality environments. However, the incorporation of HTSs in military fast-jets has occurred relatively recently and fewer studies addressing the human factors aspects of HTSs in fast-jets have been reported.

In the 1970s and 1980s, several studies were published that documented the effects of visual delay on pilot performance in fixed-wing and rotary-wing flight simulators[13-18]. These studies found that delays of simulator imagery of 80 to 150 ms degraded pilot performance or system stability. In a more recent study using an Army rotary-wing simulator, pilot performance decrements were found at 400 and 533 ms delays but not at 267 ms and lower delays[19]. There were several other interesting findings from this study. For example, no interaction between flight task difficultly and visual delay was found. In addition, there was a significant reduction of accidents in the third of three trials suggesting that pilots were adapting to the delays.

Head and hand trackers are components of virtual reality systems (VRS) that are used to determine and transmit positional information. Therefore, many of the human factors issues that are significant in the use of HTSs in military fast-jets are also important when dealing with VRSs. Numerous studies have examined visual delay in VRSs and how to alleviate the associated problems[20-24]. In an innovative human factors study, MacKenzie and Ware designed a method to examine the effects of visual delay without actually using a tracker system[21]. They had observers use a mouse to center a black dot in a target box that appeared on a CRT. Buffering and processing the mouse output added various amounts of delay to the dot's movement. They found that a 225 ms delay significantly increased movement times and error rates compared to the no-delay condition. Similar studies may be useful to determine the human factors requirements of HTSs.

The ultimate study of an HTS in a military fast-jet is to use it in the cockpit during flight. Frey and Page[6] reported the results of a study to replace the HUD with a virtual HUD (the HUD symbology was displayed on the HMD). Three display conditions (HUD, virtual HUD with off-boresight symbology, and virtual HUD without off-boresight symbology) were evaluated across several primary and secondary flying/targeting tasks. Subjective data were gathered from seven pilots who flew some or all of the tasks. The overall conclusion was that further refinement of the virtual HUD was needed. Excessive jitter of virtual HUD symbology was of primary concern. Although it was not possible to directly evaluate the impact of latency in this study, the authors stated that all latencies should be engineered to be as low as possible from the outset.

3. DYNAMIC TRACKER TEST APPARATUS EVALUATION

The Dynamic Tracker Test Apparatus (DTTA) was designed by the Helmet Mounted Sensory Technology (HMST) laboratory to accurately measure azimuth rotation in both static and dynamic conditions. The DTTA was characterized for static position data at various increments through a 360° sweep and for speeds up to 1000°/sec or 17.45 rad/sec. The following describes the design, construction, capabilities, limitations, characterization and performance of the DTTA.

3.1 System Description

The Dynamic Tracker Test Apparatus (DTTA) is comprised of components as seen in Figure 2 and Figure 3. It is constructed entirely of non-ferrous components, except for the encoder, thereby minimizing magnetic field effects if used for evaluating magnetic trackers. The set screws are standard off-the-shelf nylon except for the 0° set screw, which is nonferrous. All the principle components were custom fabricated from polycarbonate.

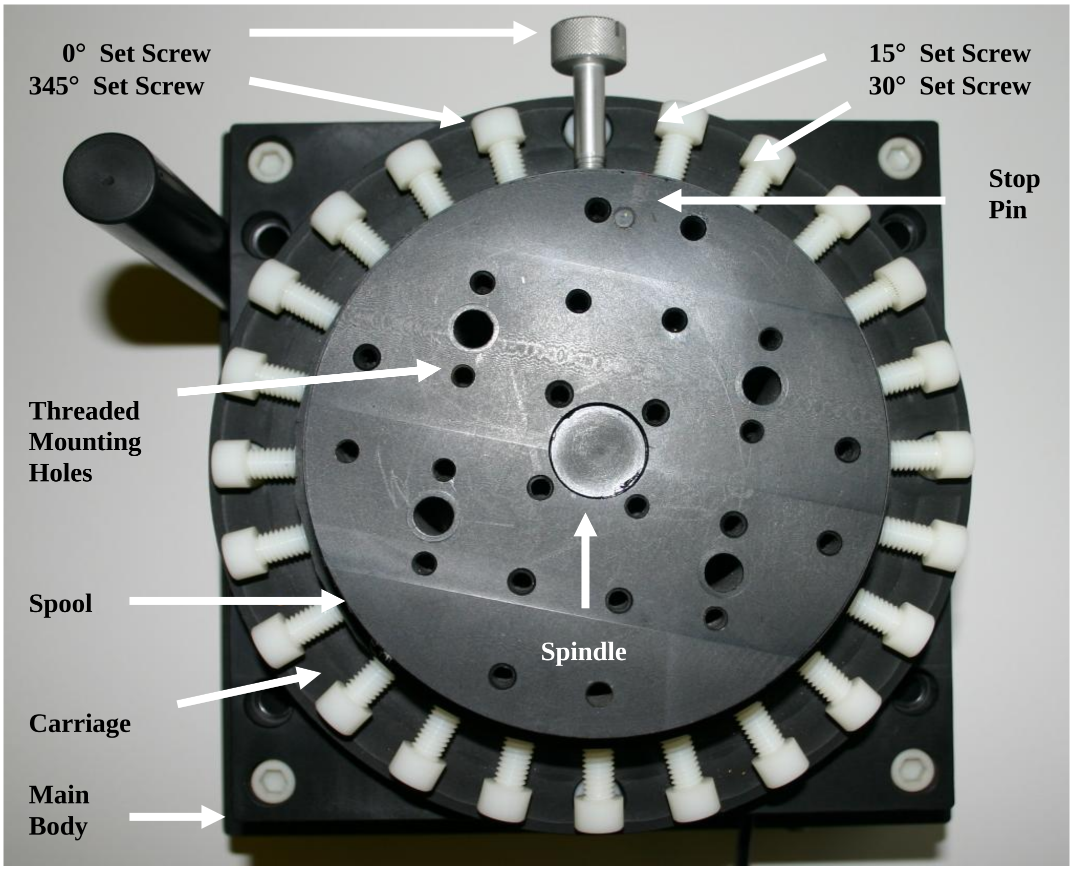

Figure 2. Dynamic tracker test apparatus (top view)

The spool is threaded about the outer perimeter and serves as a guide for the string which tethers a weight. The spool is mechanically connected to the encoder through the spindle. Both the main body and the carriage are precision bored and act as guides for the spindle as the spool is rotated. The spool is supported by the carriage through mating shouldered surfaces and it rotates freely. The top of the spool is drilled every 1" on center with ¼"-20 threads, identical to standard optical tables. This allows mounting of standard optical hardware, facilitating custom fixtures. The spool also includes a stop pin that extends into the carriage.

The carriage serves two primary functions. First, it mechanically supports the spool with a mating shouldered surface and is precision bored to help align the spindle that connects the spool to the encoder. Second, it provides a means to move and stop the spool at any combination of 15° increments about its 360° rotation when the set screws are spun in. Accordingly, the carriage is drilled and threaded about its outer perimeter every 15° to accommodate mating set screws. The set screws are a position aid; they are not intended as an exact reference point.

The encoder is a metrology-grade measurement device specifically designed for rotary tables with a resolution, after 4x quadrature decode and 50x interpolation, of 0.0001° (0.36 arc/sec) and an accuracy of ± 1.25 arc/sec. The position data output from the encoder is represented by two quadrature pulse streams that can be decoded to 3,600,000 counts per revolution. It also includes an index marker and out-of-tolerance marker. Under dynamic conditions, the encoder can accurately output data at a maximum rate of 1000 rev/min (RPM) or 104.7 rad/sec.

The index marker generates a high output signal at the same physical location with respect to the encoder's internal shaft once every revolution. This index can be used to identify the absolute beginning of a rotation (0 counts) or to determine an offset, by number of counts, from where an absolute beginning is desired. Thus, the exact starting and ending position, within 0.0001° or 1/3,600,000 counts, can be found and repeated. The out-of-tolerance marker generates a low pulse indicating faulty encoder operation.

The encoder is mounted to the main body and connected to the spool through the spindle, as seen in Figure 3. A specialized shaft coupler is used to mount the spindle to the encoder which protects the encoder if the spindle is moved side-to-side and compensates for any spindle alignment or assembly anomalies.

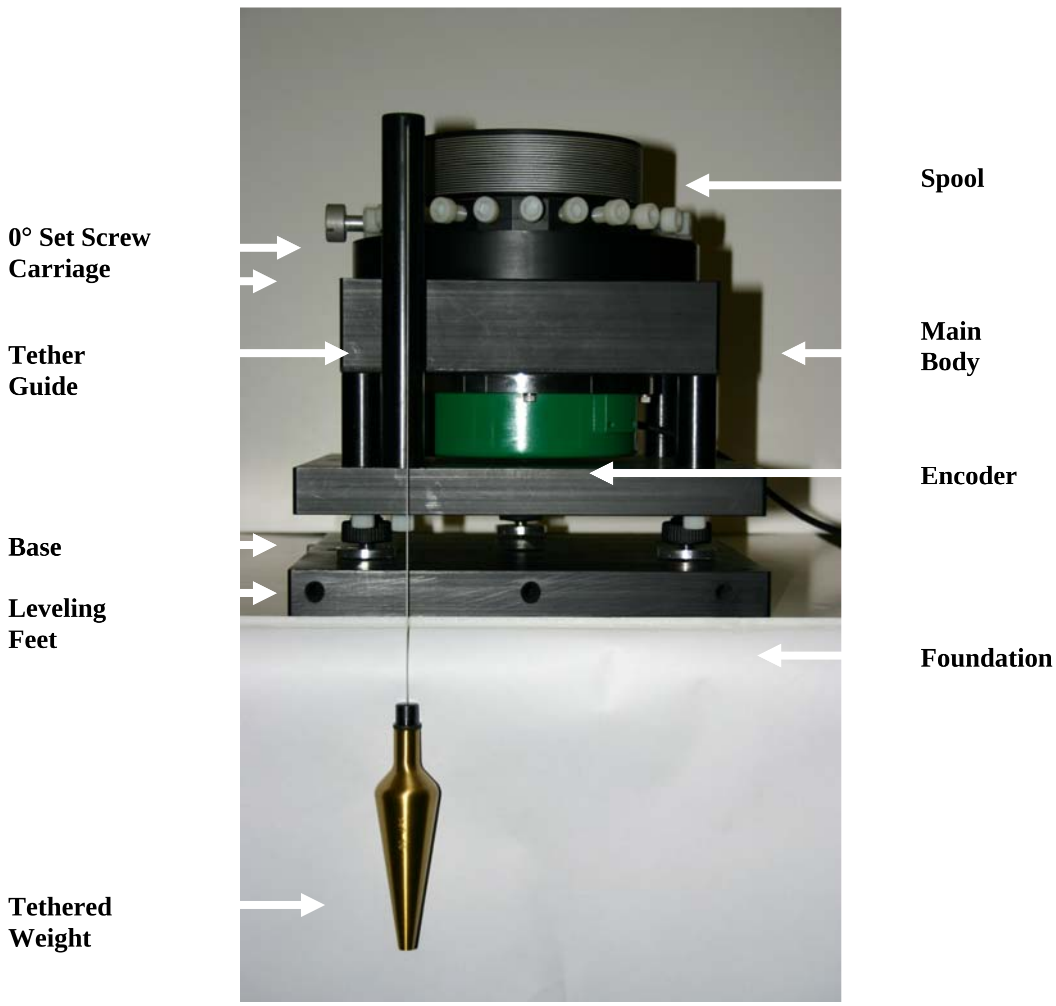

Figure 3. Dynamic tracker test apparatus (front view)

3.2 Data Acquisition

Raw quadrature data are collected from the encoder with a PCI-4E interface card specifically designed for incremental encoders. Encoder data are processed using a 24-bit real time up/down counter with a count range from 0 to 16,777,215 and are stored at approximately 150,000 samples per second to a data array. Each sample consists of four 24-bit encoder position counters and a 33 MHz time stamp. Thus, data can be collected from a static position or dynamically as it rotates. The time stamp allows computing angular velocity and/or angular acceleration.

Using the PCI-4E driver software, position data are displayed as counts displaced from the index or counts displaced from an arbitrary user established position, which is an offset amount from the index. This arbitrary position is established by the “reset” function. Data can be collected by reading the information from the display or by defining either a sampling rate, specific number of samples, or both.

3.3 System Operation

The DTTA is a mechanical device used to measure rotation about the Z axis or azimuth only. It can rotate in either a clockwise (CW) or counter clockwise (CCW) direction; however, the tethered weight (see Figure 3) only allows assisted motion in the CCW direction. The spool rotates freely in either direction, assuming all set screws are spun-out (see Figure 2). To use the DTTA in the evaluation of a head tracker system, the system’s transmitter or receiver is mounted atop the spool as shown in Figure 4. Although head tracker systems usually measure the three axes of azimuth, elevation and roll, the DTTA is only capable of measuring rotation about its vertical (Z) axis as defined in Figure 5. To make measurements in other directions, the item under test must be mounted such that the desired axis of rotation is aligned with the DTTA’s Z axis and suitable adjustments to the tracker’s complimentary transmitter/receiver/sensor made. For inertial trackers, this will be troublesome because gravity would now be affecting the wrong axis. As shown in Figure 4, an emitter pack from an optical head tracking system is mounted atop the spool in preparation for data collection. After following the head tracker system’s alignment procedure, the PCI-4E driver software is initialized. The spool can be rotated to one of the set screws or stopped at any position to make the measurement. If the set screws are used, the weight may be used to apply a constant force against them, allowing for quick placement in approximate positions every 15 degrees apart. In either situation, the encoder and PCI-4E driver software accurately display the actual position.

Figure 4. DTTA with emitter pack installed.

Figure 5. Axis of motion.

For dynamic operation, the tethered weight is used to apply a constant force in the CCW direction. With all set screws spun-out and once the weight is released, the spool will accelerate, continuing to rotate until the tethered weight stops traveling and coast to a stop. The PCI-4E driver software collects position and time stamp data.

The DTTA axes are defined as shown in Figure 5. Rotation about the **X** axis equates to a change in roll (RL), rotation about the **Y** axis equates to a change elevation (EL), and rotation about in the Z axis equates to a change in azimuth (AZ).

3.4 Static Characterization

Under perfect conditions with a perfect system, the DTTA would rotate only in azimuth (about the Z axis). Because this system is not perfect, we characterized the system to determine cross coupling between the azimuth and the elevation axis.

3.4.1 Spool characterization without head tracker equipment installed

The primary source of additional movement when the spool rotates is elevation. This movement is attributed to two factors. First, the actual flatness of the spool surface and second the straightness of the spindle that rotates the spool. The combination of these factors was measured with a mechanical dial indictor mounted at the top edge of the spool and measurements were taken as the spool was rotated. The results of these measurements are shown in Figure 6.

Figure 6 shows the average of 5 different data collection runs by two individuals. The data shows that, as the spool is rotated from -180° to +180°, the elevation varies from approximately +0.0002” to +0.0026”, which equates to an angular change of +0.07 milli-radian to +0.904 milli-radian or +/- 0.417 milli-radian from a nominal midpoint position.

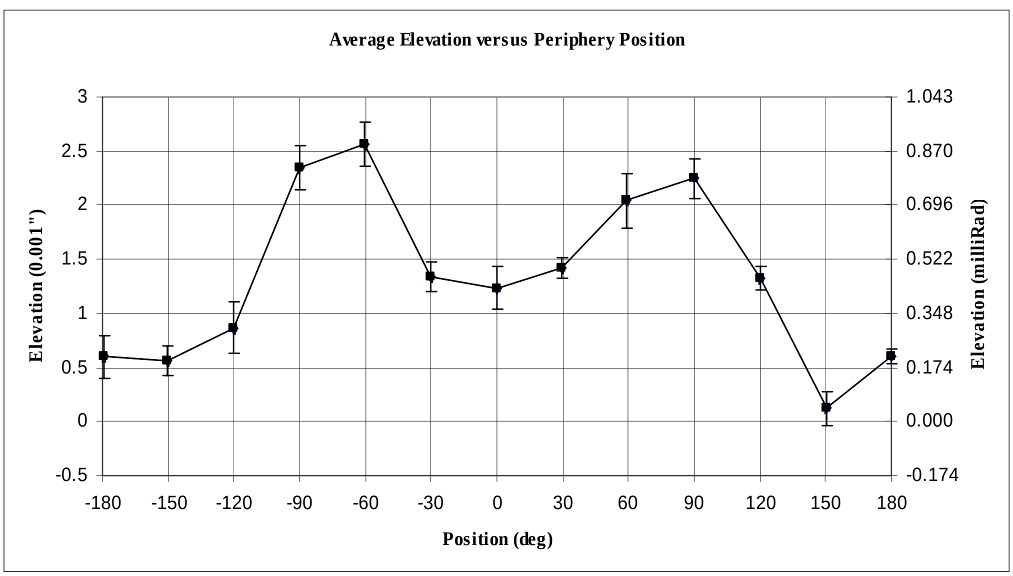

Figure 6. Average elevation versus periphery position -180° to 180°.

An additional set of data was taken to determine the “flatness” of the spool surface because it could affect the measurements. The spool was removed from the spindle and placed on a granite flat surface used for precision measurements. The same dial indicator used in the measurements described above was used for this data. The data were collected in two runs. In the first run, the spool was rotated on the granite surface while the dial indicator remained stationary. In the second data run, the spool remained stationary while the dial indicator was moved around the periphery of the spool. The data were averaged and are shown in Figure 7. The shape of this plot very closely resembles the plots from Figure 6, leading us to believe that the variation in elevation seen in the initial tests were the results of the spool's surface not being completely flat. Subtracting the results of Figure 7 from the results of Figure 6 reveals the changes in elevation due to the spindle being "out of round" or "bent". These results are shown in Figure 8. It can be seen here that the spool rotates essentially flat except for an area around the zero degree point, where the system is affected by an induced elevation change of approximately -0.0015", which equates to -522 milli-radians. The result of this reference frame misalignment from what was thought to be a "perfectly" flat plane that rotates only in azimuth is a reference frame that shows some elevation change. This misalignment results in an "induced" azimuth and elevation measurement error.

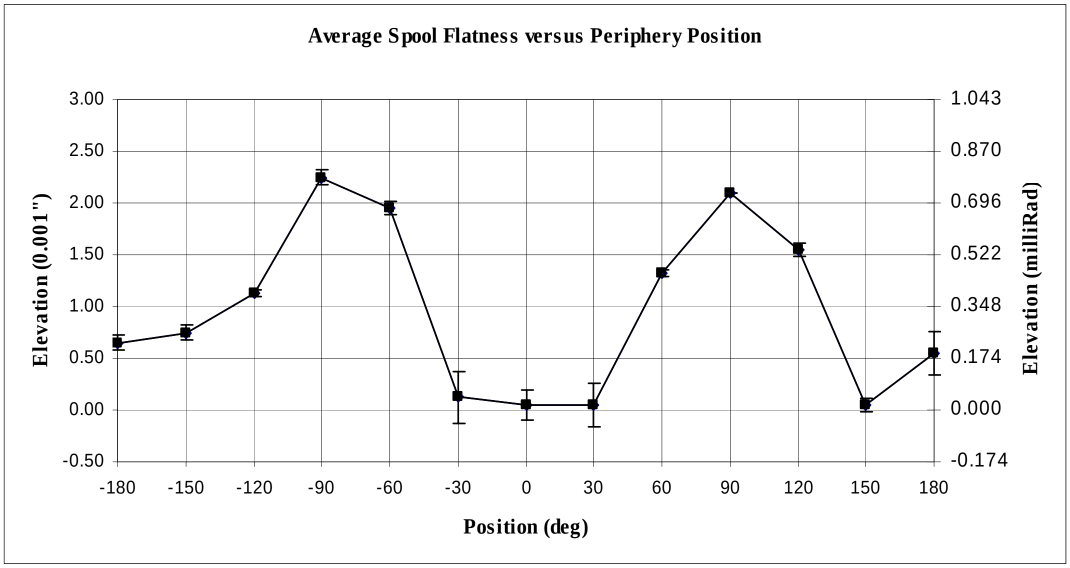

Figure 7. Average spool flatness versus periphery position.

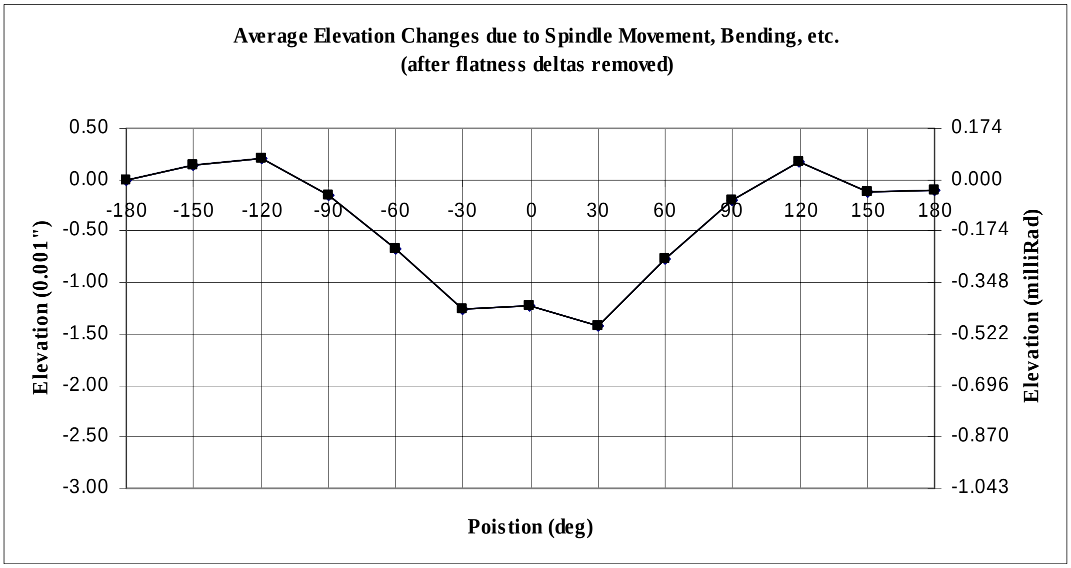

Figure 8. Average elevation changes due to spindle movement, bending, etc. (after flatness removed).

Figure 9 shows the effect of a reference frame misalignment at the same order of magnitude as seen in our system. Our system exhibited a potential misalignment, as shown in Figure 6, of approximately 1 milli-radian when combined with spool flatness. Figure 9 shows that a 1 milli-radian elevation misalignment will result in an elevation error equivalent to 1 milli-radian. (We thought the spool system rotated “perfectly” flat in azimuth, when in fact it rotated in a plane at a 1 milli-radian angle). Figure 9 also shows that this same misalignment in elevation induces an azimuth error at a maximum of approximately 1.25 micro-radians. For our system we consider this negligible.

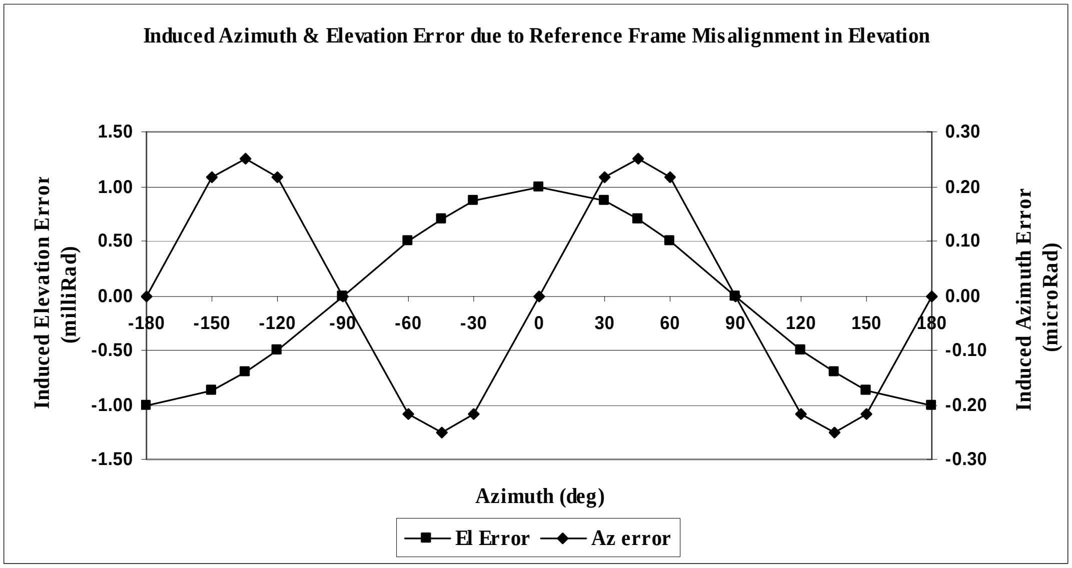

Figure 9. Induced azimuth and elevation error due to reference frame misalignment in elevation

3.5 Dynamic Characterization

3.5.1 Determination of head rotation rates

To evaluate head tracker systems under dynamic conditions, the DTTA required characterization while the spool was freely rotating. Figure 3 shows the DTTA and the tethered weight, an 8 oz brass plum bob, which provides the spool’s rotational acceleration.

Before beginning the characterization of the DTTA under dynamic conditions, a maximum target rotational speed is required. In association with the Personal Protection Branch of the Human Effectiveness Directorate at the Air Force Research Laboratory, a series of experiments were conducted to determine approximately how quickly a person could rotate their head in the Z or azimuth axis.

For each experiment, the subjects wore a pilot’s helmet with a 2 pound weight mounted near the visor to simulate the weight of an NVG and head tracker. Accelerometers were positioned about the helmet to collect data in the **X, Y,** and Z axis direction. Each subject then rotated their head several times in quick single bursts in a continual or back and forth fashion. The objective was to mimic head rotations a pilot might do while looking around inside the cockpit. A quick single burst would simulate a quick look over their shoulder or looking back and forth under surveillance conditions. The results of the experiment are shown in Table 1. From Table 1, it is seen that the DTTA should rotate at 11.64 rad/sec or greater. Another conclusion drawn from Table 1 is that, although pure rotation about the Z axis was desired, there were rotations about the X and **Y** axis in all experimental runs.

Table 1. Rates and head rotations when the head with helmet and 2 pound NVG ballast is rotated about the Z axis.

Experiment	Rotation Direction	R_Z (rad/sec)	R_Y (rad/sec)	R_X (rad/sec)
1	Positive	11.64	5.52	1.91
1	Negative	10.66	4.11	2.13
2	Positive	9.49	3.82	3.00
2	Negative	9.52	1.86	1.99

3.5.2 Dynamic characterization of the DTTA

The dynamic characterization began by elevating the DTTA to a height sufficient to allow the spool to spin 3 to 4 full rotations. These rotations allowed the tethered weight to overcome the frictional forces of the DTTA and approach a steady state velocity. Referring to Figure 10 it can be seen that there are four acceleration curves, each one increasing as read from left to right: 4.659 rad/sec, 12.843 rad/sec, 15.932 rad/sec, and 18.026 rad/sec, respectively. The accelerations are increasing as frictional forces are overcome. Several runs were made in this test and the results compared favorably.

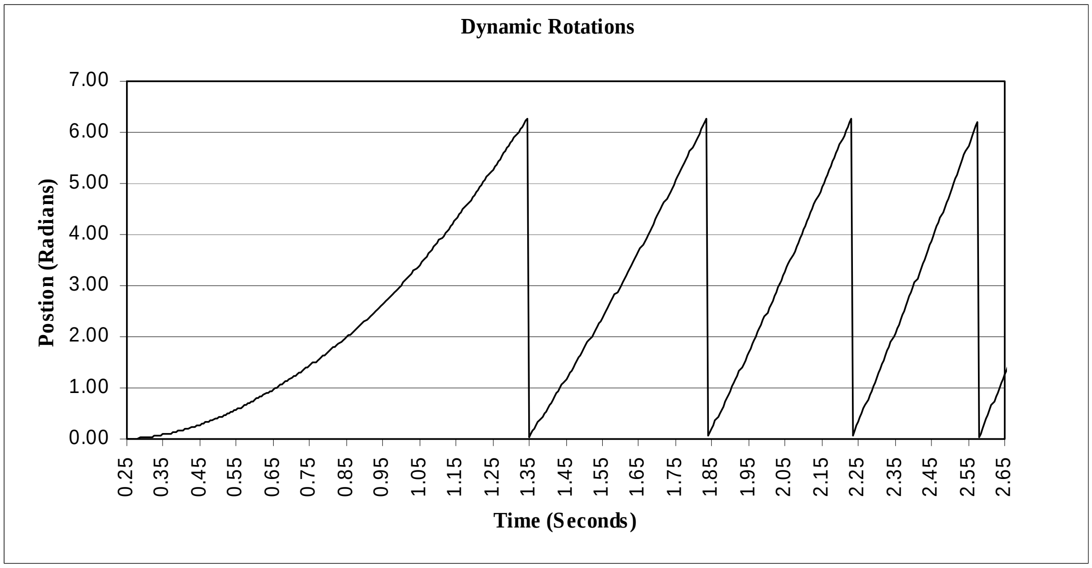

Figure 10. Dynamic Rotation of DTTA

4.0 CONCLUSIONS

The incorporation of an HTS and HMD into military fast-jets will revolutionize a pilot's ability to fly and fight. However, this undertaking is complex and not fully understood. The ideal HTS would have no noise, zero latency, and perfect accuracy. Such a system does not exist. A wide variety of human factors problems must be identified and solved before the maximum benefit of HTS technology in the fast-jet cockpit can be realized. Included among these problems are HTS noise, accuracy, and latency issues. More studies are needed to determine the requirements for these issues and other human factors issues of using an HTS in a fast-jet.

The DTTA is used to evaluate helmet-mounted trackers about the azimuth axis in a laboratory environment. The system can be used for very accurate static or dynamic measurements about this single axis. Depending on the tracker technology being evaluated, it may be possible to evaluate a tracker's other axes (elevation and/or rotation) by rotating the tracker element on the fixture such that, as the fixture rotates in azimuth, the tracker rotates about one of these other axis. It is further noted that, even though the dynamic forcing function is not accurately controlled, the measurements taken during the dynamic process are very accurate. Thus, comparisons can be made from measurement run to run by matching up velocities and/or accelerations. Several runs may be necessary to completely evaluate a tracker system in its entire operational envelope. The system offers an effective and accurate method to evaluate helmet-mounted tracker systems in both the static and dynamic environments.

5. REFERENCES

1. R. K. Osgood, M. J. Wells and D. P. Meador, "A comparison of head-steered and aircraft-fixed infrared imagery for employing the AGM-65 Maverick missile", *Proceedings of SPIE: Helmet- and Head-Mounted Displays and Symbology Design Requirements II*, R. J. Lewandowski, W. Stephens and L. A. Haworth (eds.), 2465, 184-193, SPIE, Bellingham, WA, 1995.
2. E. E. Geiselman, P. R. Havig and M. T. Brewer, "A non distributed flight reference symbology for helmet-mounted display use during off-boresight viewing: development and evaluation", *Proceedings of SPIE*, 4021, 272-283, 2000.
3. J. C. Jenkins, P. R. Havig and E. E. Geiselman, "A nondistributed flight reference symbology for helmet-mounted display use during off-boresight viewing: a dynamic task evaluation", *Proceedings of SPIE: Helmet- and Head-Mounted Displays VI*, R. J. Lewandowski, L. A. Haworth, H. J. Girolamo and C. E. Rash (eds.), 4361, 237-250, SPIE, Bellingham, WA, 2001.
4. J. C. Jenkins, A. J. Thurling, P. R. Havig and E. E. Geiselman, "Flight test evaluation of the non-distributed flight reference off-boresight helmet-mounted display symbology", *Proceedings of SPIE: Helmet- and Head-Mounted Displays VII*, C. E. Rash and C. E. Reese (eds.), 4711, 341-355, SPIE, Bellingham, WA, 2002.
5. Y. Kranz, "Latency: Requirements and implementation of ah helmet mounted cueing system (HMCS) in a fast jet", *Proceedings of SPIE: Helmet- and Head-Mounted Displays IV*, R. J. Lewandowski, L. A. Haworth and H. J. Girolamo (eds.), 3689, 135-142, SPIE, Bellingham, WA, 1999.
6. T. W. Frey and H. J. Page, "Virtual HUD using an HMD", *Proceedings of SPIE: Helmet- and Head-Mounted Displays VI*, R. J. Lewandowski, L. A. Haworth, H. J. Girolamo and C. E. Rash (eds.), 4361, 237 - 250, SPIE, Bellingham, WA, 2001.
7. F. J. Ferrin, "Survey of helmet tracking technologies", *Proceedings of SPIE: Large-Screen-Projection, Avionic, and Helmet-Mounted Displays*, H. M. Asssenheim, R. A. Flasck, T. M. Lippert and J. Bentz (eds.), 1456, 86-94, SPIE, Bellingham, WA, 1991.
8. A. A. Cameron, S. Trythall and A. M. Barton, "Helmet trackers - the future", *Proceedings of SPIE: Helmet- and Head-Mounted Displays and Symbology Design Requirements II*, R. J. Lewandowski, W. Stephens and L. A. Haworth (eds.), 2465, 281-295, SPIE, Bellingham, WA, 1995.
9. http://www.sfu.ca/sonic-studio/handbook/Noise.html, Accessed 24 Mar 2003
10. J. Cogan, "Tracker accuracy requirements and testing", *Proceedings of SPIE: Helmet- and Head-Mounted Displays IV*, R. J. Lewandowski, L. A. Haworth and H. J. Girolamo (eds.), 3689, 118-125, SPIE, Bellingham, WA, 1999.
11. B. Adelstein, E. Johnston and S. Ellis, "Dynamic response of electromagnetic spatial displacement trackers", *Presence*, 5, 302-317, 1996.
12. R. S. Kalawsky, *Critical aspects of visually coupled systems*, R. A. Earnshaw, M. A. Gigante and H. Jones (eds), 203-212, Academic Press Limited, London, 1993.
13. F. R. Cooper, W. T. Harris and V. J. Sharkey, "The effect of delay in the presentation of visual information on pilot performance", *NAVTRAEQUIPCEN IH-250*, 78 pp, Orlando, FL, 1975.
14. G. L. Ricard and J. A. Puig, "Delay of visual feedback in aircraft simulators", *NAVTRAEQUIPC-TN-56*, 44 pp, Orlando, FL, 1977.
15. S. Baron, R. Lancraft and G. Zacharias, "Pilot/vehicle model analysis of visual and motion cue requirements in flight simulation", *NASA contractor Report 3312*, 159 pp, Moffett Field, CA, 1980.
16. D. F. Crane, "The effects of time delay in man-machine control systems: Implications for design of flight simulator visual-display-delay compensation", *Proceedings of the Image III Conference*, 636, 331-343, Phoenix, AZ, 1984.
17. K. C. Uliano, E. Y. Lambert, R. S. Kennedy and D. J. Sheppard, "The effects of asynchronous visual delays on simulator flight performance and the development of simulator sickness symptomatology", *NAVTRASYSCEN-86-D-0026-1*, 74 pp, Orlando, FL, 1986.
18. K. Boettcher, D. K. Schmidt and L. Case, "Display system dynamics for flying qualities", *AFWAL-TR-88-3017*, 188 pp, Wright-Patterson AFB, OH, 1988.
19. R. M. Wildzunas, T. L. Barron and R. W. Wiley, "Visual display delay effects on pilot performance", *Aviation, Space, and Environmental Medicine*, 67, 214-221, 1996.
20. S. Bryson and S. S. Fisher, "Defining, modeling, and measuring system lag in virtual environments", *Proceedings of SPIE: Stereoscopic Displays and Applications*, J. O. Merritt and S. S. Fisher (eds.), 1256, 98-109, SPIE, Bellingham, WA, 1990.

21. I. S. MacKenzie and C. Ware, "Lag as a determinant of human performance in interactive systems", *Proceedings of the ACM Conference on Human Factors in Computing Systems - INTERCHI '93*, 488-493, ACM, New Youk, 1993.
22. J. Y. Jung, B. D. Adelstein and S. R. Ellis, "Discriminability of prediction artifacts in a time-delayed virtual environment", *Proceedings of the IEA 2000/HFES 2000 Congress*, 2000.
23. S. R. Ellis, B. D. Adelstein, S. Baumeler, G. J. Jense and R. H. Jacoby, "Sensor spatial distortion, visual latency, and update rate effects on 3D tracking in virtual environments", *Proceeding, VR '99*, Houston, TX, 1999.
24. S. Emura and S. Tachi, "Multisensor integration prediction for virtual reality", *Presence*, 7, 410-422, 1998.